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The assessment of evolutionary algorithms for analyzing the positional accuracy and uncertainty of maps

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ABSTRACT

Pre-geodetic maps are an important part of our cultural heritage and a potential source of information for historical studies. Historical cartography should be evaluated in terms of precision and uncertainty prior to their use in any application. In the last decade, the majority of papers that address multi-objective optimization employed the concept of Pareto optimality. The goal of Pareto-based multi-objective strategies is to generate a front (set) of nondominated solutions as an approximation to the true Pareto-optimal front. This article proposes a solution for the problems of multi-objective accuracy and uncertainty analysis of pre-geodetic maps using four Pareto-based multi-objective evolutionary algorithms: HVSEA, NSGAII, SPEAII and msPESA. "The Geographic Atlas of Spain (AGE)" by Tomas Lopez in 1804 provides the cartography for this study. The results obtained from the data collected from the kingdoms of Extremadura and Aragon, sheets of maps (54-55-56-57) and (70-71-72-73), respectively, demonstrate the advantages of these multi-objective approaches compared with classical methods. The results show that the removal of 8% of the towns it is possible to obtain improvements of approximately 30% for HVSEA, msPESA and NSGAII. The comparison of these algorithms indicates that the majority of nondominated solutions obtained by NSGAII dominate the solutions obtained by msPESA and HVSEA; however, msPESA and HVSEA obtain acceptable extreme solutions in some instances. The Pareto fronts based on multi-objective evolutionary algorithms (MOEAs) are a better alternative when the uncertainty of map analyzed is high or unknown. Consequently, Pareto-based multi-objective evolutionary algorithms establish new perspectives for analyzing the positional accuracy and uncertainty of maps.
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1. Introduction

Pre-geodetic maps are an important part of our cultural heritage (Jenny & Hurni, 2011) and provide a suitable cartographic base for historical urban and landscape analyses (San-Antonio-Gómez, Velilla, & Manzano-Agugliaro, 2014). These maps have traditionally been examined by historians and geographers rather than specialists in modern mapping sciences. Thus, early maps are considered to be a typical archive that serves as a historical testimony of territories and cities. In previous decades, due to advancements in new computational technologies, the study of the metric properties of old maps and the numerical approach to this issue has improved (Balletti, 2006). Currently, early maps are frequently incorporated into geographical information systems (GISs) for historical analysis (Audisio, Nigrelli, & Lollino, 2009; Hu, 2010).

Quality is a basic requirement for the users of any product. Since the 1980s, the interest in the quality of spatial data has increased due to two developments: the emergence of GIS in the 1960s and the beginning of the 1970s and a substantial increase in available spatial data from satellites. As pre-geodetic maps have limited quality, their quality must be analyzed prior to their use in historical studies. In previous decades, a large number of studies, which evaluate the quality of spatial data in early maps, have been published (Boutoura & Livieratos, 2006; Giordano & Nolan, 2007; Leyk, Boesch, & Weibel, 2005; Pearson, 2005; Ravenhill & Gilg, 1974).

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Among the components of spatial data quality, positional accuracy is the most common in academia. Traditionally, positional accuracy assessments in cartography have been based on a comparison between the positions of a set of points on a map and the positions of the same points obtained from a more accurate source (Mozas & Ariza, 2011). Positional accuracy is determined by a statistical evaluation of random and systematic errors and is specified by the root-mean-square error (RMSE) or the mean value error (μ) and their standard deviation (σ) (Ariza López & Atkinson Gordo, 2008). The International Organisation for Standardisation (ISO) considers positional accuracy to be one of the quantitative quality elements of spatial data (Ariza López & Atkinson Gordo, 2008). International Standard 19113 (ISO2002) proposes a general framework for describing and reporting the quality of geographic information, and International Standard 19114 (ISO2003) presents a general quality evaluation methodology for geographic information.

Currently, several standards complete the ISO norm and define the positional accuracy of cartographic products based on the analysis of a set of points (Ariza López & Atkinson Gordo, 2008): National Map Accuracy Standards (NMAS)-United States Geological Survey (USGS) 1947 (USA), engineering map accuracy standards (EMAS)-American Society of Civil Engineers (ASCE) 1983, accuracy standards for large-scale maps (ASLSM)-American Society for Photogrammetry and Remote Sensing (ASPRS) 1999, National standards for Spatial Data Accuracy (NSSDA)-Federal Geographic Data Committee (FGDC) 1998, and Standardisation Agreement (STANAG) 2215 (Bozic & Radojcic, 2011) by the North Atlantic Treatment Organisation (NATO).

A comparison of historical maps with contemporary maps requires additional analysis as the spatial elements and their delineations that are represented in historical documents contain considerable inherent uncertainty (Leyk et al., 2005; Plewe, 2002). The term uncertainty is more complex and extensive than the concept of accuracy. Fisher (1999) distinguished three forms of uncertainty that develop in the process of deriving a spatial data set from the real world: error, vagueness, and ambiguity. Error is defined as the difference between the value of a property of a measured object and the true value of the same property; it can only be measured for well-defined objects. Vagueness is attributed to poor definition, poor documentation, or fuzzy objects. Ambiguity stems from disagreement about the definition of objects and fundamental differences in opinion. Thus, positional inaccuracy only refers to the concept of error. The uncertainty term must be applied when accuracy is not feasible (Hunter & Goodchild, 1993).

When studying positional uncertainty in early maps, it is important to consider that uncertainty is not limited to the different stages of map production. The paper or other material used by early maps are not inert materials and maps can be deformed over the years, which alters the geometry of a map (Jenny & Hurni, 2011). Although positional accuracy and positional uncertainty are different concepts, it is often difficult or impossible to distinguish between the two concepts (Tucci & Giordano, 2011). This situation occurs when analyzing the quality of historical maps.

An additional problem in the analysis of historical cartographic quality is caused by the uncertainty of the datum and the projection on which historical maps are based. It is not always possible to know if the observed displacement between feature locations on a historical map relative to a contemporary map is attributed to inaccuracy, different geodetic reference systems, or different methods for transferring features to the map plane (Pearson, 2005).

The comparison of early maps with modern cartography allows the study of the geometric content and deformation of early maps. If the maps are expressed in different geodetic reference systems, this comparison can be performed after georeferencing the early map. Two methods for georeferencing exist: transformation between two coordinate systems, in which the transformation parameters are known, and transformation using identical ground points, in which the transformation parameters are unknown (Podobnikar, 2009). The second method is usually used to reference an early map, as only projection and datum information from the late nineteenth century is known with certainty (Pearson, 2005). In addition, the influence of the geodetic coordinate system can be neglected in the study of old maps as its effects are minor compared with positional uncertainty (Jenny & Hurni, 2011).

Thus, a comparison between early and contemporary maps can be performed using best-fitting techniques of different schemes for relevant transformations of sets of points on an early map to corresponding sets of points on a modern reference map (Boutoura & Livieratos, 2006). The transformation can comprise a global transformation, which alters the coordinates of the control points after the transformation, or a local transformation, which retains the coordinates of the control points (Balletti, 2006). The global transformations are derived from a polynomial system of equations. The commonly employed global transformations consist of conformal, affine, and projective linear transformations and polynomial (usually second-order) transformations. Local transformations consist of finite element transformations and transformations that are typically referred to as feature-based warping (Balletti, 2006). An affine transformation between geographic coordinates are used in this study. Using five parameters, this transformation considers rotation, horizontal, and vertical scale errors and latitude and longitude displacements.

A crucial aspect of obtaining transformation parameters is the election of common points in early maps and reference maps (Podobnikar, 2009), which should be carefully chosen as erroneous control points can alter the comparisons of maps. Here, we must consider the heterogeneous positional uncertainty of early maps. Some control points may correspond to different spatial positions, possible landscape changes, and, a priori, we do not have criterion to identify them.

Multi-objective evolutionary algorithms are known for their ability to simultaneously optimize several objective functions to obtain a representative set of the Pareto front (Baños, Gil, Reca, & Martìnez, 2009; Márquez et al., 2011; Voorneveld, 2003). The goal of Pareto-based multi-objective strategies is to generate a front (set) of nondominated solutions as an approximation to the true Pareto-optimal front (Alcayde et al., 2011). The majority of papers that have addressed multi-objective optimization employed the concept of Pareto-optimality to perform a comparison among several genetic algorithms (Anagnostopoulos & Mamanis, 2011; Baños, Ortega, Gil, Fernández, & de Toro, 2013; Fernández, Gil, Baños, & Montoya, 2013; Gómez-Lorente, Triguero, Gil, & Estrella, 2012) or traditional analyses (Dovgan, Javorski, Tušar, Gams, & Filipic, 2013; Sánchez, Montoya, Manzano-Agugliaro, & Gil, 2013).

Previous studies show that the evolutionary algorithm msPESA is a viable alternative for transforming historical map coordinates, particularly where the quality of the position of the set of points to be used for the transformation cannot be assured (Manzano-Agugliaro, San-Antonio-Gómez, López, Montoya, & Gil, 2013). The aim of this study is the assessment of different evolutionary algorithms to determine the gross error in the control points and the accuracy of pre-geodetic maps. These algorithms will be evaluated using the Geographic Atlas of Spain (AGE) produced by the Spanish cartographer Tomás López (1730–1802). The AGE comprises an anthology of maps of Spanish regions that were drawn in the second half of the eighteenth century; it is the most ambitious and successfully completed cartographic work (Manzano-Agugliaro, Fernández-Sánchez, & San-Antonio-Gómez, 2013). These pre-geodetic maps (San-Antonio-Gómez, Velilla, & Manzano-Agugliaro, 2011) exhibit substantial heterogeneous positional uncertainty (Chias and Abad).

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